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Citation: Brüne, Markus, Charlton, James, Pflitsch, Andreas and Agnew, Brian (2016) The Influence of subway climatology on gas dispersion and the effectiveness of guided evacuations in a complex subway station. Meteorologische Zeitschrift, 25 (4). pp. 489-499. ISSN 0941-2948

Published by: Schweizerbart

URL: https://www.schweizerbart.de/papers/metz/detail/pr... <https://www.schweizerbart.de/papers/metz/detail/prepub/86503/The_Influence_of_subway_climatology_on_gas_dispersion_and_the_effectiveness_of_guided_evacuations_in_a_complex_subway_station?l=EN>

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Meteorologische Zeitschrift, Vol. 25, No. 4, 489–499 (published online July 7, 2016)
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Environmental Meteorology

The Influence of subway climatology on gas dispersion and the effectiveness of guided evacuations in a complex subway station

Markus Brüne[1*], James Charlton[2], Andreas Pflitsch[1] and Brian Agnew[3]

[1]Workgroup Cave and Subway Climatology, Department of Geography, Ruhr-Universität Bochum, Germany
[2]Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, NE1 8ST, United Kingdom
[3]NewRail, School of Mechanical and Systems Engineering, University of Newcastle upon Tyne, Newcastle upon Tyne, NE17RU, United Kingdom

(Manuscript received July 20, 2015; in revised form December 17, 2015; accepted December 21, 2015)

Abstract

This paper discusses a strategy that integrates data from tracer gas experiments with results from pedestrian simulation software in the evaluation of different evacuation procedures for subway stations in response to a fire or a terrorist attack with chemical, biological, radiological, nuclear and enhanced conventional weapons (CBRNE). The study demonstrates that by combining the two data sets a greater understanding of the impact of different evacuations routes on an evacuee's health is gained. It is shown that by controlling the routes pedestrians would use to exit a subway station, the number of fatalities and evacuees with long term health issues can be reduced. It is highlighted that a dynamic evacuation guiding system based on subway climatology would take into account the source of the toxin, the resulting dispersal of gas, smoke, etc. and the subway climatology at the time. In doing so, it would be possible to identify the most endangered areas and guide passengers via an adaptive escape route using audio and visual techniques. Information on the evolution of the emergency situation could also simultaneously be relayed back to the rescue forces to help to plan the rescue and evacuation procedures and optimise the deployment of the search and rescue teams.

Keywords: pedestrian simulation, gas attack, subway climatology, tracer gas experiment, guided evacuation

1 Introduction

The key question of this research is to examine the evacuation capabilities of one of the most frequented stations within Berlin, in the event of a terrorist attack with chemical, biological, radiological, nuclear and enhanced conventional weapons (CBRNE). Previous research carried out as part for the project "Cross-organizational hazard prevention to protect human life and critical infrastructures by optimised prevention and reaction" (OrGaMIR), funded by the German Ministry of Research and education (BMBF), examined the interchange stations Hermannplatz, Berliner Straße and Osloer Straße (Pflitsch, 2011). It was shown that the internal chimney effect plays a major role in the dispersion of airborne toxins that may very quickly reach exits via staircases making them unsafe as an escape route (Pflitsch et al., 2013). The subsequent OrGaMIR^{plus} Project, of which this study is part, is now focused on the biggest rail interchange within Berlin, Alexanderplatz. As a result of the high number of passengers who use the subway station on a daily basis, it is potentially a vulnerable and an attractive target for terrorist attacks. Furthermore, the complexity and numerous options of exit routes can lead to inefficient and disorganised exit procedures. The internal Handbook of emergency management (Berliner Verkehrsbetriebe, 2005) of the Berlin subway operator (BVG) suggests for chemical or biological attacks that passengers will be instructed to leave the subway station immediately by the advice of operator's employees. Specific evacuation routes during the self-rescue phase are not defined. However, the numerous possible exit routes also allow the station to offer a more controlled evacuation plan via pre-defined routes based on the evacuation scenario.

This paper will discuss an initial pilot study examining the evacuation capabilities of Alexanderplatz in response to a terrorist attack with airborne hazardous substances. Results from tracer gas experiments will be combined with simulated results from pedestrian modelling software to assess different evacuation procedures during an emergency situation. The combined results will be used to compare and evaluate evacuation procedures based on free choice or pre-defined routes. The individual strands of research based on a case study of Alexanderplatz are discussed, before combined results are highlighted and conclusions and possible future research are considered.

This study is part of an overall research project focused on the development of an intelligent safety sys-

*Corresponding author: Markus Brüne, Workgroup Cave and Subway Climatology, Department of Geography, Ruhr-Universität Bochum, Universitätstraße 150, 44801 Bochum Germany, e-mail: markus.bruene@rub.de

© 2016 The authors
DOI 10.1127/metz/2016/0726
Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

tem for transportation hubs to allow the diagnosis and evaluation of an emergency situation in order to supply information for decision makers and evacuees. It is envisaged that such a system would help to formulate the rescue and evacuation procedures by identifying areas to concentrate the rescue teams, identifying the most endangered areas and providing an adaptive escape route system for the passengers. This is a relatively new area of research as until recently the natural airflow regime in subway systems was widely unknown (Pflitsch and Küsel, 2003).

2 Case study Berlin Alexanderplatz: climate measurements and tracer gas experiments

The subway station Alexanderplatz (see Figure 1) is located in the centre of Berlin and is the most used interchange station in the city. Built from 1910–1913 according to the plans by Alfred Grenander, the underground station originally only consisted of one line but from 1926 to 1930 two additional lines were added, also built according to Grenander's conception. Today the subway station still consists of these three subway lines, the North and South running U2 and U8 and the East and West running U5. Alexanderplatz subway station is also directly connected to a heavily used national train station of the same name.

2.1 Subway climatology

The relatively young research field of "Subway Climatology" was developed in the late 1990s by Pflitsch who postulated that the airflow in subway systems behaved in a similar way to that in cave systems (Pflitsch and Küsel, 2003). Subway systems are characterized by very few connections to the outer atmosphere. Consequently, subway systems develop their own specific local climatology: shortwave heating and long wave radiative cooling processes are absent and the soil heat flux is significantly higher due a higher surface volume ratio and a higher ground temperature in urban agglomerations. Additionally, the anthropogenic energy release from trains, technical equipment and passengers have to be taken into account. On the other hand energy loss due to latent and sensible heat transfer is highly reduced and long wave radiation is trapped in an underground building. These factors cause a general over-warming of subway tunnels compared to the outer atmosphere from late summer to winter. Penetrating cold air and rising warm air at the subway system's openings to the outer atmosphere drive natural air flow in the tunnels. Therefore, in the event of a terrorist attack with CBRNE substances inside a subway station or a fire, such climatology would have a major effect on the dispersion of any airborne substances released (Brüne et al., 2012; Pflitsch et al., 2010).

2.2 Climate measurements

Since December 2011 as part of the OrGaMIR^{plus} project air flow has been continuously measured in each tunnel corresponding to three subway lines. These measurements, using ultrasonic anemometers (A and B Figure 3), showed that at all tunnel entrances there was a very small inflow of air from the tunnel portals into the station. Occasionally higher air flows were observed especially at the eastern tunnel entrance (B), shown in Figure 3. The track terminates at the western end of tunnel entrance (A) resulting in a weak flow at this location.

The climatology measurements gathered were in accordance with what was expected for the time the experiment was conducted. This first experiment was set up during the nightly operational break in order to avoid the influences of train traffic and to not disturb the passengers. Future experiments will be performed during operational times and might be based on numerical simulations (computational fluid dynamics). This will make the scenario more realistic and give the opportunity to calculate the effectiveness of evacuations routes coupled with the dispersion of toxic gases for operational times and other conditions (Wang and Chen, 2008; Epstein et al., 2011). Nevertheless, tracking the propagation paths of toxic gases in infrastructures should go hand in hand with empirical measurements, especially when results are used for safety purposes. During the night, train traffic does not disturb air flow, so thermal effects play a major role. Due to natural convection, warmer air masses naturally move upwards, which was displayed clearly by the portable anemometers III, V and VI (see Figure 2) that were installed for the tracer gas tests. Two sets of stairs (east and west) connect the two platforms on level 4 to the mezzanines on level 3; a central stairway further connects each mezzanine level to level 2. Therefore, air masses flow from both sides of each mezzanine level towards the middle escalator and up to level 2. This is observed on both sides (east and west).

2.3 Previous tracer experiments

Previous to this research several tracer gas experiments were carried out by the authors at several subway stations in Berlin (Pflitsch et al., 2010; Pflitsch et al., 2013). Sulphur hexafluoride (SF_6) was used, as it is non-toxic, odourless, invisible and easily detectable due to its very low occurrence in the atmosphere of 0.005 ppb. Experiments could be done without endangering the passengers or the researchers. SF_6 is six times heavier than air, but previous experiments proved that it mixes very rapidly with air and closely follows the air movement (Pflitsch et al., 2010). The tracer gas was released from a gas cylinder containing liquefied SF_6, researchers were allocated to appropriate measurement points and were tasked with filling 60 ml syringes with the local air at one minute intervals. The syringes were closed with a rubber plug and the air was examined by gas chromatography afterwards.

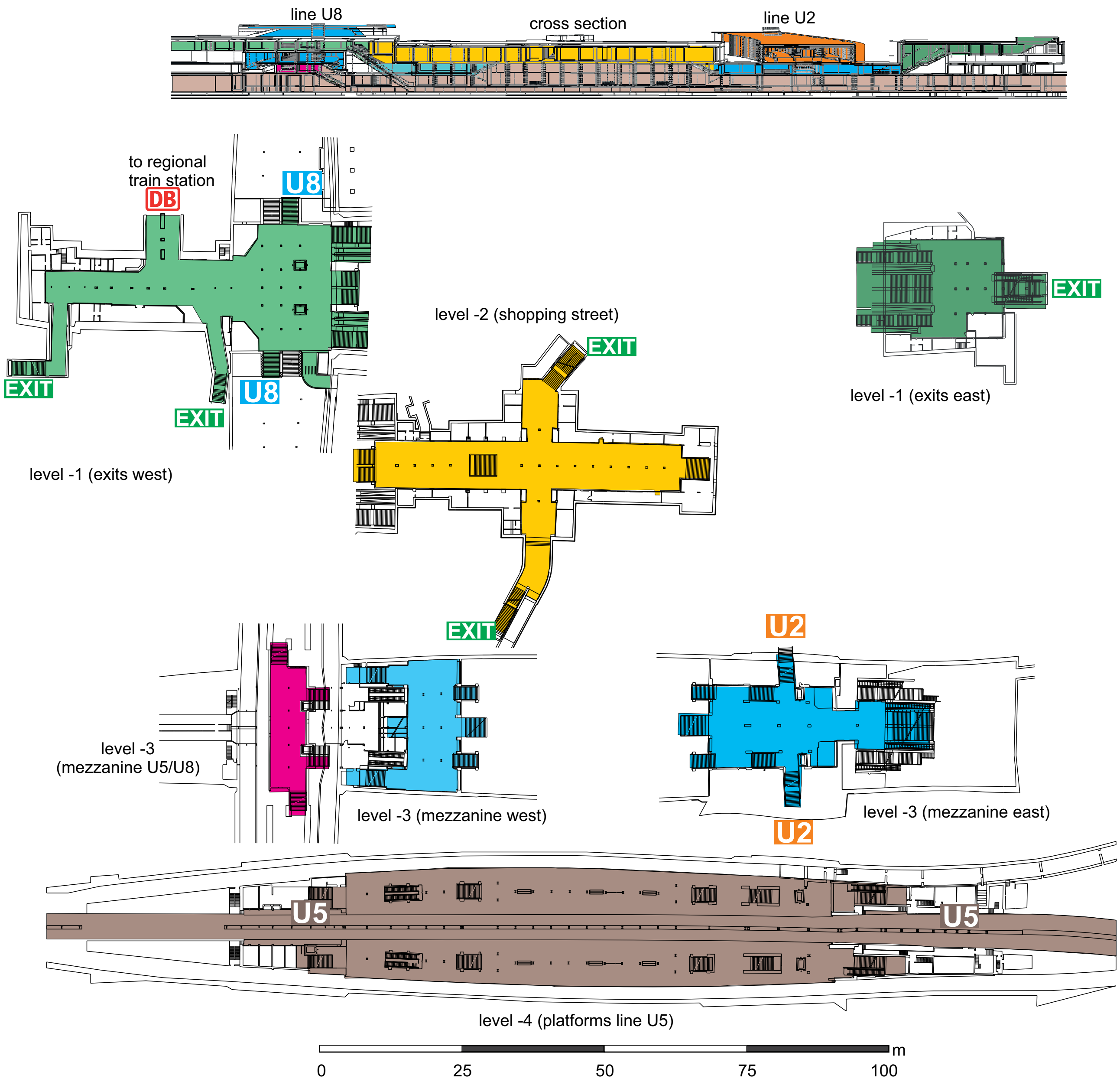

Figure 1: Overview of subway station Alexanderplatz, top: cross section, bottom: plan views.

2.4 Tracer gas dispersion

The tracer gas data presented in this paper is based on a single tracer gas experiment carried out on 6 December 2011 at 02:16 (MEZ) and is only valid for the prevailing weather conditions. It has been proven by Pflitsch and Küsel (2003) that the natural air flow through subway tunnels is not constant, resulting in a changing air flow situation within subway stations. However, this limitation does not distract from the aim of this paper to show how combining results from tracer gas experiments with pedestrian simulations can be used to assess evacuation procedures for underground stations during an emergency situation.

For the period of the tracer gas experiment six additional mobile ultrasonic anemometers where placed at the mezzanines on level −3 to measure the air flow inside the subway station (see Figure 2). The mobile measurements mostly showed up streaming air masses from the U5 platforms (level −4) to the mezzanine west (III) and the mezzanine east (V, VI). The exception to this was at location IV on the mezzanine west, where it can be assumed that descending cold air played a major role (see Figure 6). Penetrating cold air downstream was also observed and measured in previous work (Brüne et al., 2012).

Following the release of 4 kg of SF_6 gas over a 2 minute period, readings were recorded at each of the 21 measurement points throughout the subway station (see Figure 4). The first high values were observed only 4 minutes after the start of the release at measurement point 8, located on the mezzanine west, with a reading of 1090 ppb (see Figure 5). At the same time a greater

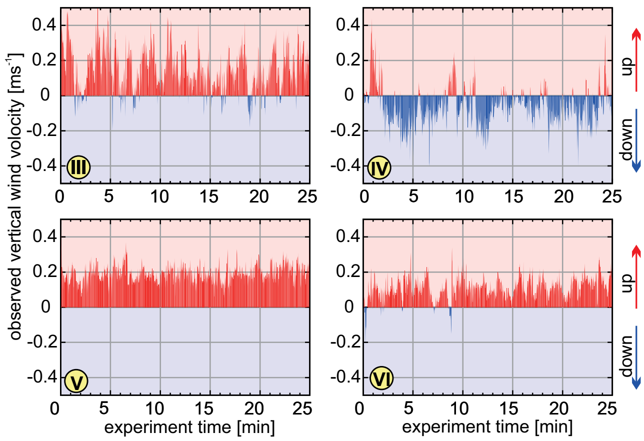

Figure 2: Vertical air flow measured with mobile anemometers at the mezzanines on level −3. Locations of measurement points see Figure 4.

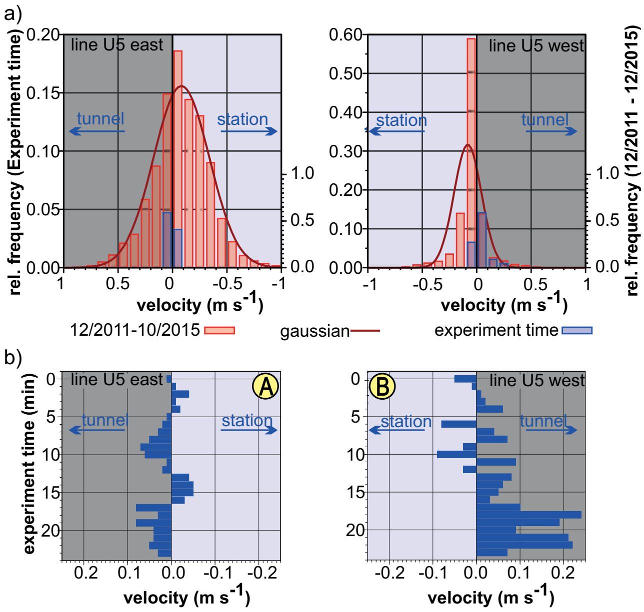

Figure 3: a) Distribution of measured air flow during operational breaks at the tunnel entrances on level −4 (line U5) during the experiment time and long term observations (December 2011 to October 2015). b) Airflow observed during the experiment.

contamination reading was recorded in the higher lying shopping street level at measurement point 16, with a reading of 6630 ppb. Five minutes after the release, the contamination values dropped at the western side, whilst they rose on the eastern side. This is a result of higher and more stable air flow towards the tunnel twelve minutes into the measurement (see Figure 3), so the SF_6 cloud shifted to the western parts of the station. This explains the average dispersion of SF_6, illustrated in Figure 15.

In the remaining areas of the subway station, including the lowest level (level −4) where the gas was released, readings lower than 1000 ppb were recorded for a period up to 6 minutes following the start of the release. After this period of time, significantly high readings were recorded for measurement points 5 and 14 located on level −4 and the east mezzanine level −3, respectively. These values stayed high for the remaining duration of the experiment. In contrast, over a similar time frame, recordings at measurement points 8 and 16 began to fall. Recordings at measurement point 16 gradually fell from 5 minutes after the release, while recordings at measurement point 8 remained high before falling more dramatically after 11 minutes.

Compared to Figure 5, the initial lack of build-up of tracer gas on level −4 is related to the dimensions of this space. The ceiling of platform U5 is more than 5 m high and measures 36 m at its widest point level −4. The large dimension of this space forms a large hall where the tracer gas accumulated at the ceiling due to convection and in spite of its high molar mass. The sensors on the U5 platforms were placed approximately 1.5 m above the ground so the SF_6 was not initially recorded. But approximately six minutes after release the platform areas were filled with the tracer gas and significant concentrations reached the instruments and the recorded values at point 5 began to rise.

The results from the tracer gas show that due to the point of release and the climatic situation found within the station at that time, the majority of the gas dispersed up from level −4 via the west mezzanine on level −3 towards the shopping street located on level −2. This occurred within the first 5 minutes after release. This pathway of high contamination can be linked to the staircase from level −4 to level −2 being relatively open (see Figure 6), allowing SF_6-contaminated air mass to move upward very rapidly due to the thermal buoyancy effect and accumulate in the shopping street with its low ceiling of 2.3 m. This resulted in the concourse area and the stairways linking level −4 to level −2 being heavily contaminated.

3 Case study Berlin Alexanderplatz: pedestrian simulations

To examine the evacuation capabilities of Alexanderplatz, the study adopted the use of an agent based pedestrian simulation software called Legion SpaceWorks. Agent-based pedestrian modelling software is capable of representing the attributes and behaviour of individual agents within given environments (Castle, 2006). For example, agents can be assigned varying degrees of prior knowledge regarding a buildings layout (e.g. commuters vs. tourists), different mobility (e.g. children, adults, impaired, runner, etc.), or different global origins (e.g. Europe, UK, Asia, North American, etc.). The characteristics of these options are stated by Berrou et al. (2007) as the physical radius of each entity, the speed profile drawn from preferred speeds of real pedestrians in similar locations and context and the personal space (oriented in the direction of movement) surrounding each entity, also drawn from a distribution of measurements

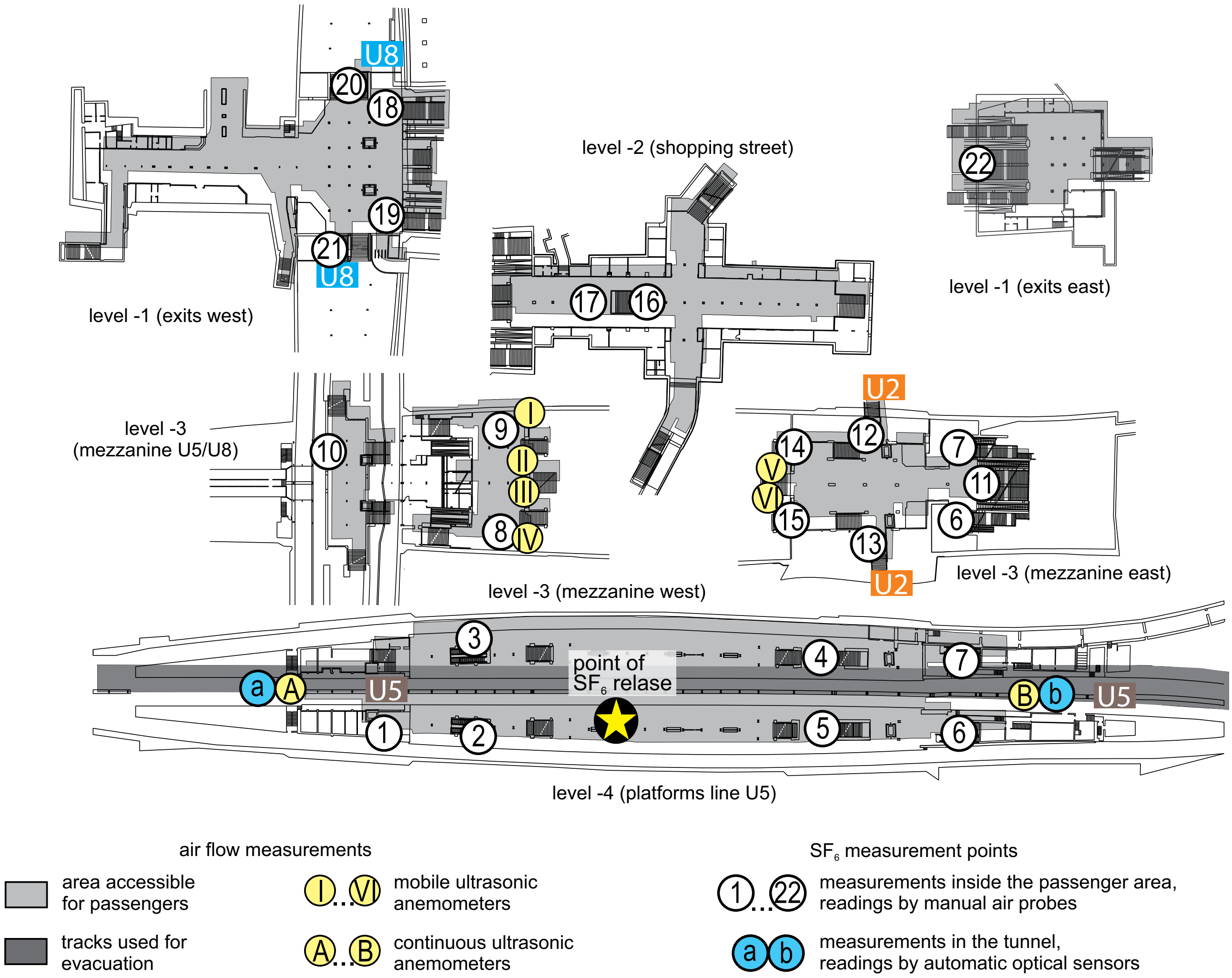

Figure 4: Position of anemometer and tracer gas measurement points.

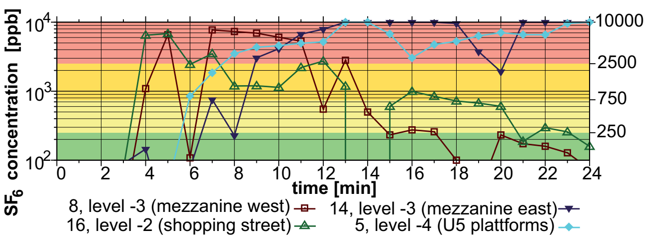

Figure 5: Timeline of SF_6 values of selected measurement points. Locations of measurement points see Figure 4.

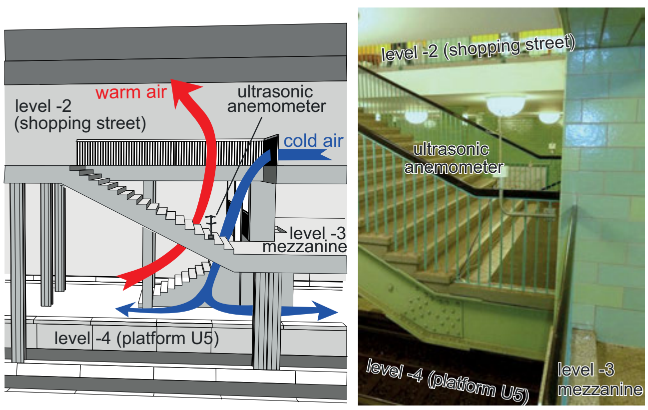

Figure 6: Possible movement of air masses inside the station. 3D-model (left) and picture (right) of the staircase connecting level −4, −3, −2.

on real people. These are also sensitive to local conditions (crowding or lack thereof), context (stairs, escalators), and projected intentions of neighbours.

Legion SpaceWorks, which supersedes the original Legion Studio, has been found to be the most advanced and realistic simulation model available for micro-level pedestrian analysis (Helgason et al., 2010; Charlton, 2011) following a comprehensive review of agent-based software. Primarily used by architects and civil engineers, one of the greatest innovations from Legion Studio is that in Legion SpaceWorks users are no longer required to define the paths the agents take, but instead only define the origin and exit point of the pedestrian. Route modifiers (stairs, flat paved areas, bottlenecks), are then added to the model to trigger a change in the movement, activity or destination of the pedestrian, al-

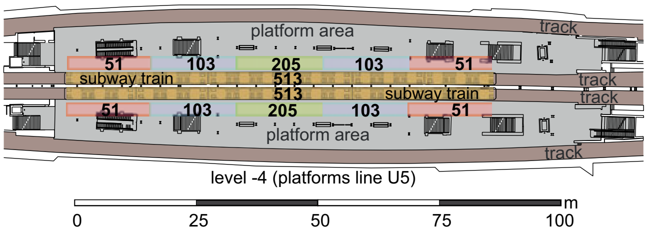

Figure 7: Number of agents on their starting positions on level −4 within the pedestrian simulation model.

lowing for a more organic and realistic pedestrian flow to be achieved. In the past Legion SpaceWorks has been used to perform virtual experiments on the design and operation for railway stations, sports stadiums, airports, transport hubs, etc. to assess the impact of different physical designs or levels of pedestrian demand.

3.1 Creating a pedestrian simulation model of Alexanderplatz

Using a 3D SketchUp model of Alexanderplatz, 2D CAD plans of each platform and concourse areas within the station were extracted for use within Legion SpaceWorks. Following the importation of these plans, 2048 agents were placed throughout the lowest level (level −4) to represent the highest demand found on these platforms, as defined by the German Federal Railway Authority (Blennemann, 2005). Of the 2048 agents 236 were located on each platform, distributed as shown in Figure 7, and 788 agents were distributed evenly throughout each of the trains. The simulation represented a scenario where two trains arrived at the same time, with waiting commuters on both platforms. At the same moment an incident resulting in the release of a toxic agent occurred. The characteristics for each of the agents were configured to represent Northern European commuters. The agent's reaction time to an alarm sounding were defined in accordance with British Standards for a transportation hub (British Standards Institution, 2004) which refers to six key categories of fire evacuation analysis; alertness, familiarity, building type, staff training and alarm type. In accordance with these guidelines, in each of the scenarios simulated, no agents reacted to the alarm sounding in the first 90 seconds, the majority of the agents reacted at around 165 seconds and all agents had reacted within 240 seconds.

3.2 Assessing possible evacuation routes

With an accurate 2D model of Alexanderplatz set up within Legion SpaceWorks, three different scenarios were simulated to assess the egress from the station: 1) Agents have free choice to find the shortest route chosen by Legion SpaceWorks out of the station based on the characteristics of the agents; 2) Agents are guided along pre-defined paths by blocking certain evacuation routes which have become contaminated and are now deemed unsafe; 3) Agents were guided through the adjacent tunnels to reach the nearest emergency exit.

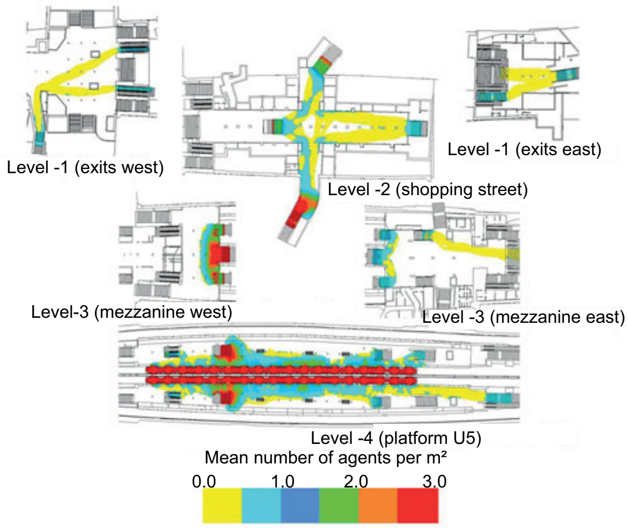

Figure 8: Simulation "free choice": cumulative mean density map.

The "free choice" simulation shows, that the majority of the agents chose to exit using the central stairs at either end of the platform, via level −3 and exiting on level −2 (see Figure 8). Only a small percentage of the agents selected to use the escalators that ran directly from level −4 to level −1. The agents that chose to exit via the west central stairways were quickly subjected to congestion on level −4. This congestion was sustained for several minutes and spread to the west central stairway located on level −3 as more and more agents tried to evacuate via this route. Following the evacuation from level −4, the agents were able to remain at a consistent speed while exiting the model.

In the second simulation, "predefined exit" agents were guided to the relevant stairs at the far west side of level −4. Agents continued up these sets of stairs until they reached level −1 where they were navigated to use only one predefined exit located on the south side of level −1 west (see Figure 9). Although this route had be chosen to prevent agents exiting via routes highly contaminated with lethal gas, the limited number of exits resulted in high levels of congestion, most significantly for those agents located on platform 2. This resulted from agents attempting to exit the model via only one exit. Agents exiting via the defined route from platform 2 became obstructed by those agents exiting from platform 1 (see Figure 10). The obstruction resulted in a build up of agents from platform 2 on the selected stairs ways, resulting in no significant movement from agents exiting from platform 2 for a period of 3 minutes.

In the third simulation, "adjacent tunnels" agents were guided along the subway tunnels connected to level −4 to emergency exits located 140 m from either end of the platform. Agents were allowed to choose which exit they considered the nearest (see Figure 11). This simulation showed that following some initial con-

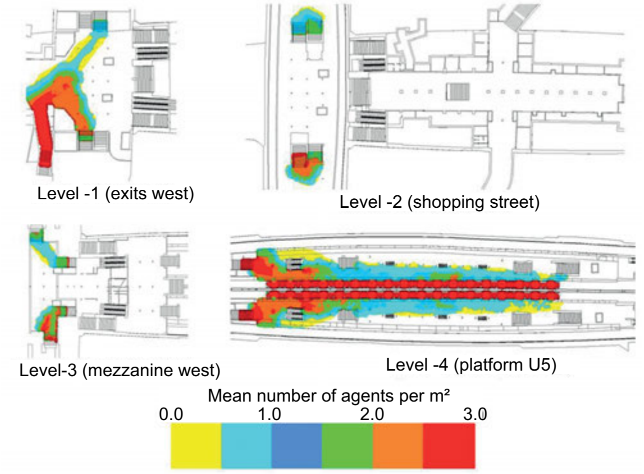

Figure 9: Simulation “pre-defined exit”: cumulative mean density map.

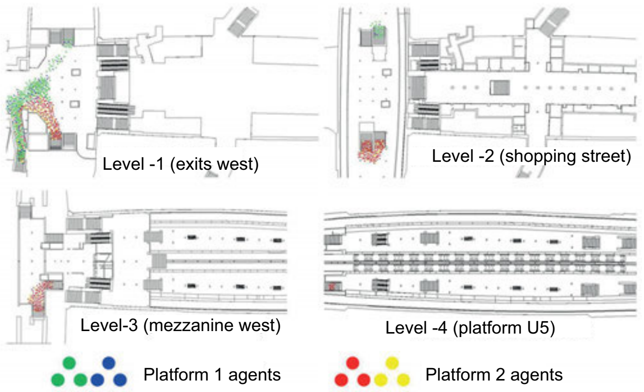

Figure 10: Simulation “pre-defined exit”: obstruction caused by agents exiting from platform 1.

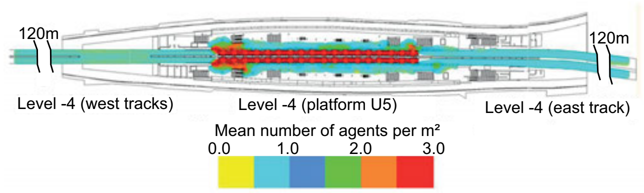

Figure 11: Simulation “adjacent tunnels”: cumulative mean density map.

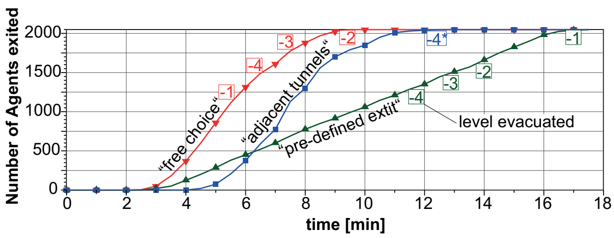

Figure 12: Egress from Alexanderplatz under different simulations.)* In simulation “adjacent tunnels” agents evacuated through level −4 only.

gestion as agents tried to exit from the platform to the tunnels, agents were able to move at a consistent speed and were able to exit the model with relative ease. The most significant congestion was created by those agents trying to exit using the west exit. This was due to the proximity of the trains in relation to the end of the platform. In comparison to the east side of the platform, where a larger gap was found between the trains and the end of the platform (19.8 m), agents exiting via the west exit were only able to progress through a 2.9 m gap.

The egress times for each of the simulations are summarized in Figure 12. It is shown that the agents were able to exit Alexanderplatz the quickest when they had free choice to decide to take the shortest route. Agents were slowest to exit the model when they were guided on pre-defined paths. In the “pre-defined” simulation in particular it took 17:05 minutes for all the agents to exit the model, even though the first agents began to exit the model in a comparable time to the agents in simulation “free choice”. This significant increase in time is a result of the congestion caused by agents exiting platform 1 and blocking agents exiting from platform 2 (see Figure 10), due to the agents only being able to exit via one exit. The resulting bottleneck caused agents exiting via the pre-defined route from platform 2 to make no significant movement for a period of 3 minutes. In the “adjacent tunnel” simulation agents were able to clear the platform within 8:15 minutes, held up slightly due to the proximity of the trains to the end of the platforms. However, due to the distance the agents needed to travel to reach their exit point, it took 12:33 minutes before all agents had exited the model.

4 Evaluating the effects of gas dispersion on evacuation routes

The simulations discussed in sections 2 and 3 showed the individual results from both tracer gas experiments and pedestrian evacuation simulations based on Alexanderplatz, respectively. Although the path of the dispersed gas has been established, it has not been shown how this data relates to the location of the agents within the separate simulations. It is known that agents are able to exit Alexanderplatz the quickest when they have free choice. But, results from the tracer gas experiment have shown that this route is the most contaminated by SF_6 gas. Therefore it is unknown how many of these agents would be subjected to lethal levels of gas for a significant period of time to cause serious long lasting health issues or even death. Therefore, the study aimed to combine the results from the tracer gas experiments with the pedestrian simulation data to highlight how such data could be used to aid in the development of a safety system for transportation hubs.

4.1 Initial examination

From simply overlaying the outputs from the pedestrian simulation with the contamination maps produced from

Figure 13: Concentration and position of agents in simulation 1 and 2, 5 min after release.

the tracer gas experiments it is possible to carry out an initial examination of those agents which may have been exposed to high levels of gas. This was calculated by assuming a respiratory minute volume of 8 l, a value for resting humans, so for fleeing people the inhaled amount of gas might be significantly higher. Figure 13 shows the position of the agents from the simulations “free choice” and “pre-defined exit” after 5 minutes, against the corresponding contamination map. It is clear that those agents which have chosen the quickest route “free choice” have also moved through the areas of high contamination located on the west mezzanine on level −3 and the shopping street located on level −2. In the “pre-defined exit” simulation where agents were restricted to exit level −4 by only one set of stairs on each platform, the resulting congestions means that there are more agents still on the platforms level (line U5) at this time. However, as explained in Section 2.4 there was no significant contamination on this level in the first 6 minutes following of the release of the gas. Although the agents exit via a less contaminated route, the evacuation time is nearly doubled in comparison to simulation “free choice”, due to this confined route and limited exits allowing significant congestion to build up. Therefore from this initial examination it is unclear what problems the increased exposure time of 17 min could cause.

In “adjacent tunnel” simulation agents escaped through the subway tunnels joined to the platforms on level −4. Results from the pedestrian simulations show that the platforms are cleared in around 8 minutes. As tracer gas results show that the concentration of SF_6 does not increase to high levels on the platforms during this time, most agents would have not inhaled any gas. But the evacuation of agents via subway tunnels is not always a feasible option. The evacuation through subway tunnels involves walking on the tracks which is only safe if there is no train traffic and the live rail (if present) is deactivated. This evacuation route is also not designated for self-rescue and would instead need to be guided by operator personal. As such a route may not always be an option, this study concentrated on further examining the other simulations. By focusing the study

Table 1: Chemical properties of SF6 and Phosgene and the mass equivalents causing the same concentration levels

Chemical properties molar mass	SF_6 146.05 g mol^{-1}	Phosgene 98.92 g mol^{-1}
density gas	6.63 kg m^{-3})^{a,b}	4.53 kg m^{-3})^{c}
boiling point 2	−64 °C	7.44 °C
EU classification		Very toxic T+
equivalents Mass	4.0 kg	2.709 kg
Particle number	27.387 mol^{-1}	27.387 mol
volume gas	613,851)^{a,b}	613,851)^{a,c}
Volume liquefied		1928 cm^{-3}

^{a} $T = 0\,°C$ ^{b} $P = 1013$ hPa ^{c} $T = 15\,°C$

on two feasible options, a free choice route and a controlled route, a more detailed examination can be carried out with regard to the safety of each route. From the initial examination it remains unclear whether a shorter but more contaminated route would be more problematic compared to a longer but less contaminated route. However, Legion SpaceWorks allows for the time (every 0.6 seconds) and location (x, y and z coordinates) of each agent throughout the simulation to be exported as a workable raw data file. The SF_6 concentrations were interpolated for each level of the whole subway station with the inverse distance method. By knowing both the position of each agent using data outputted by the pedestrian simulations and the changing concentration levels of SF_6 throughout the station, it is possible to calculate the amount of gas inhaled by each agent as they move through the model. This will provide a more definitive understanding of how the choice of evacuation route could affect the agents health.

4.2 Phosgene instead of sulfur hexafluoride

As previously mentioned, to get an understanding of how gas released from a CBRNE attack would disperse throughout the station, SF_6 was used as a tracer gas. If the results were converted to phosgene ($CClO_2$) instead of SF_6, about 2.7 kg phosgene is needed to have the same contamination values as 4 kg of SF_6. If liquefied 2.7 kg of phosgene occupies a volume of approximately 2 litres it can be easily carried in a cooled container (see Table 1). Today phosgene is most commonly used in the production of polycarbonate. It gained infamy as a chemical weapon in World War I (Spiers, 2010). The World Health Organisation estimates a world production of up to 3 billion tons in 1997 (MacConnell, 1997). According to the Acute Exposure Guideline Levels (AEGL) of the US Environmental Protection Agency two values can be used for this case study:

> **AEGL-2** is the airborne concentration [...] of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
>
> **AEGL-3** is the airborne concentration [...] of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.
>
> (AEGL, 2002)

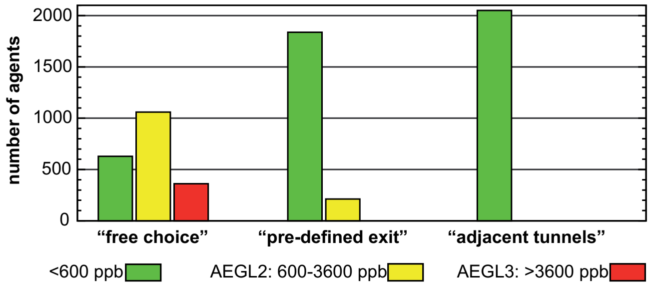

Figure 14: AEGL Level (equivalent to 10 min exposure) agents reach in different simulation.

Phosgene AEGL-2 and AEGL-3 have a value of 600 ppb and 3600 ppb, respectively, validated for an exposure period of 10 min. Based on an agent's choice of exit route, the interpolated SF_6 concentration along this route and the time it takes for the agent to evacuate from the station, each agent was assigned an equivalent concentration level to 10 minutes of phosgene exposure. This process allows for the cumulative amount of inhaled phosgene to be calculated for each agent and to compare the cumulative value to the validated AEGL-2 and AEGL-3 exposure periods. In doing so, the number of agents reaching and surpassing these values could be estimated. Figure 15 shows the position of agents when they reach the AEGL-2 and AEGL-3 level for the different evacuation simulations.

Based on the results shown, a safety assessment of different evacuations was made from the total numbers of agents reaching the different levels. Figure 14 summarizes these results and indicates the number of agents that exceed the two levels. As expected from the initial examination, in simulation 1 the agents using the west staircases between the platforms U5 and the shopping street begin to exceed the AEGL-2 level when they were on the west mezzanine level. Those agents that are slow to respond and as a result are caught in the congestion that builds on these staircases are also the first agents to reach the deathly AEGL-3 level in this location. As the evacuation continues, more deaths are expected on the shopping street level. From the completed study, the results show that in simulation 1, around 350 agents will die during an evacuation of Alexanderplatz, whilst more than one thousand will have long-lasting health issues. This study could not take into account the possibility that those agents that exceed AEGL-2 level of contamination may become impaired resulting in increased con-

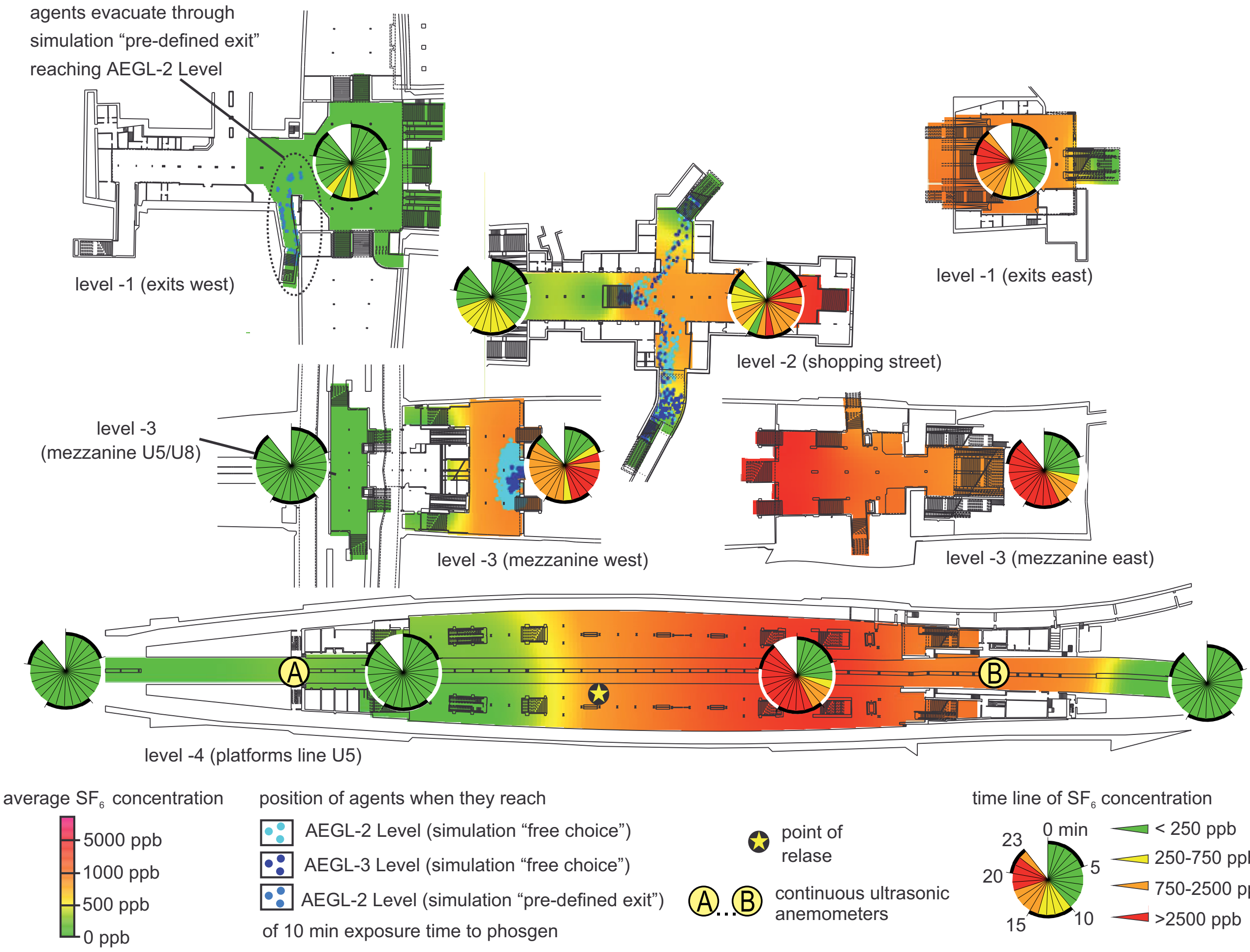

Figure 15: Average SF_6 distribution, timing sequence of SF_6 contamination and position of agents (Simulation 1 and 2) when they reach the equivalent AEGL-2 or AEGL-3 level (Acute Exposure Guideline Levels) (AEGL, 2002).

gestion. Immobilized or dead agents may become obstacle for the other agents. Therefore it is expected that the number of deaths could be significantly higher than predicted. In the second simulation, even with the low contamination, due to the long evacuation time, it was established that over 200 agents will exceed the AEGL-2 level before they are able to exit the subway station, but no agents will exceed the AEGL-3 level. The combined tracer gas results and pedestrian simulation shows that all the agents that exceed the AEGL-2 level will do so in the congestion build up on level −1 as they try to exit via a single exit (see Figure 15). However, although one single exit was defined in simulation 2, level −1 west contains two possible exits. It can therefore be assumed that if both exits were used, the congestion build up on Level −1 west would not be so severe, allowing for the agents to exit faster, reducing the number of agents that exceed the AGEL-2 level.

In comparing the two simulations it is clear that agents exiting via a controlled, pre-defined route are able to do so in the safest manner, regardless of the increased evacuation time. The results show that the majority of the agents in simulation 2 were exposed at a level below 600 ppb and no agents exceeded the AGEL-3 level and therefore no agents would have died exiting via this route. This is in agreement with the work by Gross (2015).

5 Conclusion

This study has shown that different evacuation routes in Alexanderplatz station have different risk levels. The tracer gas dispersion which established the risk levels presented in this paper were based on only one sample test. It has been proven by Pflitsch and Küsel (2003) that the natural air flow through subway tunnels is not constant and changes according to outer atmosphere conditions, temperature and moisture difference between underground and over ground air. This constant change in atmospheric conditions results in a fluctuating climatology within subway stations. Although the presented results are therefore only valid for this particular air flow situation measured at the tunnel portals (see Figure 3), it has been shown how a guided evacuation could reduce the number of deaths and injuries in a case of a terrorist attack with chemical warfare. Generally it was shown that staying in lower levels for as long as possible could be a good strategy to leave the area of risk even if it takes longer. Tsukahara et al. (2011) who examined the Daegu subway fire in 2003 came to the same conclusion. They suggest a deeper subway level underlying the lowest platforms for evacuation which is not applicable due to high building costs. It can therefore be proposed that a dynamic evacuation guiding system based on subway climatology is a more applicable solution and as such should be taken into account in designing new automatic evacuation systems. Such systems would consider the location and cause of the evacuation, the resulting dispersal of gas, smoke, etc. and the subway climate at the time. In doing so, the system could identify the most endangered areas and guide passengers via an adaptive escape route using audio and visual techniques. In catastrophic circumstances people want to go out to the over ground as quickly as possible, so intelligent evacuation systems may guide people against their natural flight behavior. Information on the evolution of the emergency situation could also simultaneously be relayed back to the rescue forces to help to plan the rescue and evacuation procedures, by being able to answer questions as to where to concentrate the rescue teams. The development of such a system forms the main aim of the OrGaMIR project and is where future research will lie.

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